ASCA Observations of the Thermal Composite Supernova Remnant 3C 391

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ABSTRACT

We present the results from ASCA observations of the centrally enhanced supernova remnant 3C 391 (G31.9+0.0). We use the *ASCA* SIS data to carry out an investigation of the spatial and spectral properties of the X-ray emission from this remnant. The collisional equilibrium ionization and non-equilibrium ionization spectral fits indicate that the hot gas within the remnant has basically reached ionization equilibrium. The variation of the hydrogen column density across the remnant is in agreement with the presence of a molecular cloud to the northwest. The comparisons of hydrogen column and X-ray hardness between the NW and SE portions of the remnant support a scenario in which the SNR has broken out of a dense region into an adjacent region of lower density. The mean density within the SNR is observed to be much lower than the immediate ambient cloud density. This and the centrally brightened X-ray morphology can be explained either by the evaporation of engulfed cloudlets or by a radiative stage of evolution for the remnant.

Subject headings: radiation mechanisms: thermal — supernova remnants: individual: 3C 391 (G31.9+0.0) — X-rays: ISM

1. Introduction

Apart from the well-known classification of shell-like, Crab-like, and composite supernova remnants (SNRs), a collection of SNRs with shell-like radio emission and centrally brightened thermal X-rays has attracted substantial attention (e.g., White & Long 1991 [=WL91]; Rho & Petre 1998; Wilner, Reynolds, & Moffett 1998). Many of these so-called "thermal composite" or "mixed morphology" remnants (such as W28, W44, IC 443, G349.7+0.2, and 3C 391) are found to produce the hydroxyl radical 1720 MHz maser emission that is characteristic of a shock interaction with dense molecular gas (Green et al. 1997).

3C 391 (G31.9+0.0) is similar to other remnants in this collection. Its X-ray brightness peaks well inside the radio shell, and the spectrum is that of a thermal plasma. The remnant shows an elongation from northwest (NW) to southeast (SE) in the radio band, and the centroid of the soft X-ray emission lies in the SE region. Reynolds & Moffett (1993) (= RM93) first pointed out that the radio and X-ray morphologies can be explained with a gas breakout from a molecular cloud into a lower density region. In a *ROSAT* X-ray study, Rho & Petre (1996) (= RP96) could not actually distinguish between an increase in hydrogen column density or a decrease in temperature across the remnant from SE to NW from the spectra alone, and favored the hydrogen column variation based on the morphology. Frail et al. (1996) suggest that OH masers in the direction of 3C 391 are associated with the remnant, and Reach & Rho (1996) find strong enhancement in [OI] emission near the northwestern edge of the remnant, which is indicative of shock interaction. CO and other molecular line observations confirm the location of the remnant at the southwestern edge of a molecular cloud (Wilner et al. 1998; Reach & Rho 1999). The far-infrared H_2O and OH emission lines are consistent with the passage of shock wave through dense clumps (Reach & Rho 1998), and broad CS and CO line sources are found to coincide with one of the OH maser regions (Reach & Rho 1999).

Because of the limited spectral resolution of the *ROSAT* PSPC (0.5-2.2 keV) and *Einstein* IPC ($< 4\,\mathrm{keV}$), the previous X-ray instruments did not resolve line features in the SNR spectrum. *ASCA*, with its broader energy range (0.5-10 keV) and better energy response, allows us to analyze

the line emission, element abundances, and the narrow band images to investigate the physics of the hot gas inside 3C 391 and inspect the breakout model more fully.

2. Data Analysis

The *ASCA* observation of 3C 391 was made on 21-22 April 1994 with both the solid-state imaging spectrometer (SIS) and the gas imaging spectrometer (GIS). In the SIS observation, both 1-CCD and 4-CCD clocking modes were used. The observational data were screened with the standard "rev2" criteria (see *ASCA* ABC guide). The SIS0 and SIS1 bright mode data were exploited in this analysis due to the better spectral and spatial resolution of the SIS data over the GIS data. The relevant observation parameters are listed in Table 1a.

2.1. Spectral Analysis

The spectra for the whole remnant (shown in Figure 1) were extracted from a circular region of a radius 3.5 arcmin, centered at R.A. = $18^h49^m28^s.3$, decl. = $-00°56'15''$ (J2000) (see the diagram in Figure 3a below). Background spectra were extracted from a nearby source-free field. The net count rates of the two CCD mode SIS0 and SIS1 spectra are tabulated in Table 1b. Since data of different clocking modes have different spectral responses, we would not merge the spectra but fit them simultaneously to the same model.

In order to search for spectral variations across the remnant, we also extracted spectra from two circular regions of radius 1.7 arcmin in the NW and SE halves (as diagramed in Figure 3a). The net count rates of these spectra are also tabulated in Table 1b. All the spectra mentioned above were regrouped to contain at least 25 net counts per bin.

There are three prominent line features in the spectra. To determine accurately the energy of the lines, following Bamba et al. (2000), we first fitted the spectra of the whole remnant to a thermal bremsstrahlung and three Gaussian lines with a Morrison & McCammon (1983)

interstellar absorption. The best-fit line centers are 1.35 ± 0.01, 1.85 ± 0.01, and $2.46 \pm 0.02\,\mathrm{keV}$ (the errors are 90% confidence). They correspond to Mg Heα, Si Heα, and S Heα emission lines. The Fe L complex at 1-1.5 keV could be present in the spectra. The emission diminishes rapidly above the photon energy $\sim 4\,\mathrm{keV}$ and no Fe Kα emission is observed, indicating that the gas temperature is not very high assuming normal abundances (below 1 keV). We used an absorbed collisional equilibrium ionization (CEI) model, VMEKAL (Mewe, Kaastra, & Liedahl 1995), in the XSPEC code to fit the two clocking mode SIS0 and SIS1 spectra of the whole remnant simultaneously. In the spectral fitting, the abundances of the elements (Mg, Si, & S) showing evident emission lines, are treated as free parameters, while other element abundances are fixed at the default solar values. The spectral fit for the whole remnant are shown in Figure 1. Similar fit procedures are also applied to the spectra of the NW and SE portions individually. We find no significant contribution of a high energy tail that might be associated with a strong nonthermal component to the spectrum. The CEI fit results are summarized in Table 2.

On the other hand, we also fit these spectra to VNEI, a non-equilibrium ionization (NEI) model, in the XSPEC11.0 code. The NEI fit results are presented in Table 3. The goodness-of-fit and most of the fit parameters are similar for the CEI and NEI cases, and the ionization parameter $n_e t$ obtained from the NEI models is $> 10^{12}\,\mathrm{cm}^{-3}\,\mathrm{s}$, so the hot gas in the remnant is basically in ionization equilibrium.

The metal abundances yielded with both the CEI and NEI models (see Tables 2 & 3) are essentially consistent with solar values and thus seem to be consistent with an interstellar composition. From the two tables we can not see significant difference in temperature between the SE and NW regions of 3C 391 in either model, but find different error ranges of N_{H} for the two regions (with higher N_{H} in the NW than in the SE). To check this, we compute the two-dimensional error contours for N_{H} and kT for the SE and NW regions (Figure 2). In both the CEI and NEI cases, the confidence contours for the two regions are clearly disjoint, so kT and N_{H} highly correlated for each region. The contours show similar range of temperature but different range of column density for the two regions. We also fit the NW and SE spectra simultaneously

to the same temperature and the same column density, respectively, using a CEI model; here the metal abundances for the two regions given in Table 2 are used. The best-fit results are summerized in Table 4. For the case of the same temperature, one would again see that the one dimensional error ranges of N_{H} for the two regions do not overlap. Assuming the same column density, on the other hand, leads to another possible case in which the NW region is higher in temperature but lower in emission measure than the SE. In the latter case, considering the immediate adjacency of the molecular cloud to the northwest of the remnant (Wilner et al. 1998), it is quite unlikely that the gas density the NW region is lower than that in the SE region, so the hot gas in the defined circular NW region should actually occupy larger volume than in the SE region. Though this possibility can not be eliminated, a variation in column density between the SE and NW region, ie., an increase in column density from the SE to the NW is consistent with the proximity of the molecular cloud.

2.2. Spatial Analysis

The SIS0 observation covers the entire remnant, but the SIS1 observation misses a small part of the eastern rim. We have thus used only SIS0 data for the image production. The corrections for exposure and vignetting were made for the two clocking modes (1-CCD and 4-CCD) separately, and an adjustment was made to the reconstructed pointing direction to correct for documented erroneous star-tracker readings (Gotthelf et al. 2000). The hard (2.6-10 keV) emission gray-scale image is overlaid with the soft (0.5-2.6 keV) emission contours in Figure 3a. The "hard" emission was extracted above the 2.6 keV so as to not include the lines of Mg Heα, Si Heα, and S Heα and can basically be regarded as thermal continuum. In Figure 3b and Figure 3c, the 1.5 GHz radio contours (from Moffett & Reynolds 1994) are overlaid with the soft and hard emission images, respectively. We also present the narrow band Mg Heα (1.2-1.5 keV), Si Heα (1.7-2.0 keV), and S Heα (2.3-2.6 keV) images in Figure 3d, Figure 3e, and Figure 3f. The three energy ranges (ER1, ER2, and ER3), in which the narrow band emissions are extracted, are labeled in Figure 1. The three narrow band images contain 2308, 2587, and 833 counts, individually. Note that the three

images are not corrected for the underlying continuum contribution and the Mg band (ER1) also includes emission from the Fe L blend. The Mg, Si, and S emissions have 56%, 55%, and 36% energy contributions, respectively, in each energy range. All these image maps have been adaptively smoothed so as to contain a minimum of 50 counts in the top hat filter. The two OH maser points (Frail et al. 1996) are labeled in the maps.

3.   Discussion

3.1.   Absorbing hydrogen

Both the CEI and NEI models give a hydrogen column density $N_{\rm H}$ around $3.0 \times 10^{22}\,{\rm cm}^{-2}$ (Tables 2 & 3). In the spectral fits above, we show disjoint error ranges of $N_{\rm H}$ for the NW and SE regions of 3C 391, and favor a variation in $N_{\rm H}$ between the two regions. This is consistent with the northwestward enhancement of CO emission (Wilner et al. 1998) and with the southeastward breakout scenario (RM93). In the CEI model fit, the best-fit value of $N_{\rm H}$ for the NW portion is $\sim 4 \times 10^{21}\,{\rm cm}^{-2}$ higher than that for the SE portion; and in the NEI model fit, this difference is $\sim 6 \times 10^{21}\,{\rm cm}^{-2}$. If the difference of $N_{\rm H}$ for the two portions reflects the density contrast between the inside and outside of the molecular cloud, the molecular column inside the cloud would be $N({\rm H_2}) \sim 3\text{-}4 \times 10^{20}\,{\rm cm}^{-2}$ (following RM93, considering that the photoionization cross section for H_2 at $1\,{\rm keV}$, per H atom, is about about 8 times that for atomic hydrogen [Brown & Gould 1970]). In this way the mean molecular density inside the cloud would be $\langle n({\rm H_2})\rangle \sim 100 l_{\rm pc}^{-1}\,{\rm cm}^{-3}$, where $l_{\rm pc}$ is the depth in pc of the molecular layer. This would imply $\langle n({\rm H_2})\rangle$ of order $\sim 10\text{-}20\,{\rm cm}^{-3}$ if the line-of-sight depth of the SNR in the cloud is similar to the remnant radius (6-9 pc).

3.2.   Images

The soft band map (Fig.3a,b) is very similar to the *ROSAT* PSPC image (RP96). The hard X-ray image (Fig.3a,c) looks relatively bright in the NW compared with that in the SE, in contrast

to the soft X-ray image which looks faint in the NW. This fact can be explained by increased extinction from the NW cloud, and is consistent with a model in which the gas in the SE region has broken out into a lower density environment. There seems to be a narrow X-ray bridge-like structure at the center of the X-ray images connecting the SE and NW portion, which might possibly represents the "nozzle" or "tunnel" of the NW-to-SE breakout.

The emission dominated by Mg and Si (Fig.3d,e) is centrally brightened in the SE half but faint in the NW (similar to the soft band map), implying obscuration in the NW half. An arc-like feature emerges in the NW of the S Heα emission map (Fig.3f), while it is absent in the Mg emission map (Fig.3d) and marginally evident in the Si emission map (Fig.3e). This is consistent with an absorption effect in the softer Mg and Si lines. This arc-like shaped feature is close to the NW radio shell and reveals a hot gas structure behind the blastwave and embedded in the dense cloud.

In each X-ray map the SE half is centrally brightened. The hard emission (continuum) in the NW is also centrally brightened, and is conspicuously faintest along the western limb where the radio brightness is a maximum. The mechanism responsible for the enhanced central emission may be interior cloudlet evaporation (WL91) or, perhaps, the cooling of the rim gas (e.g. Harrus et al. 1997, Rho & Petre 1998, Cox et al. 1999, Shelton et al. 1999). We discuss these two mechanisms in §3.4).

The peak of the X-ray brightness distribution is located at about R.A. = $18^{\rm h}49^{\rm m}33^{\rm s}.5$, decl. = $-00°56'37''$ (J2000) for both the soft map and the narrow band maps, and the hard map peaks at about R.A. = $18^{\rm h}49^{\rm m}25^{\rm s}$, decl. = $-00°54'32''$ (J2000). The association of 3C 391 with a dense molecular cloud is suggestive of a massive progenitor star. The gravitational core collapse of the massive progenitor should have left behind a compact star, such as that observed for IC 443 (Olbert et al. 2001), another "thermal composite" which is similar to 3C 391 in many aspects. While the broad spatial response of ASCA prohibits a sensitive search for an embedded compact star, future *Chandra* and *XMM* observations near the peaks in the soft and hard maps mentioned above are clearly of interest.

3.3. Distance

The presence of the HI absorption against 3C 391 out to the tangent point velocity $\sim +105\,\mathrm{km\,s^{-1}}$ puts the remnant beyond $7.2\,\mathrm{kpc}$ (for a Galactocentric radius $8.5\,\mathrm{kpc}$), and the absence of the absorption at negative velocities sets an upper limit of $11.4\,\mathrm{kpc}$ (Caswell et al. 1971; Radhakrishnan et al. 1972; RM93). This range is supported by the discovery of two OH 1720 MHz maser features (at $+105$ and $+110\,\mathrm{km\,s^{-1}}$) in the direction of 3C 391 (Wilner, Reynolds, & Moffett 1998). With the hydrogen column density ($N_{\mathrm{H}} \sim 3 \times 10^{22}\,\mathrm{cm^{-2}}$) obtained from the X-ray spectral fits, one can estimate another upper limit to the distance. The extinction per unit distance within $2\,\mathrm{kpc}$ in the direction of 3C 391 is $\langle E_{B-V} \rangle / d \sim 0.60\,\mathrm{mag\,kpc^{-1}}$ (Lucke 1978). The extinction beyond $2\,\mathrm{kpc}$, in the direction of the Galactic center, should be higher than this value. The correlation $N_{\mathrm{H}} = 5.9 \times 10^{21} \langle E_{B-V} \rangle\,\mathrm{cm^{-2}}$ (Spitzer 1978; Predehl & Schmitt 1995) then gives $d \lesssim 8.5\,\mathrm{kpc}$, which is in agreement with the above range of distance. In this paper $d \sim 8d_8\,\mathrm{kpc}$ will be used hereafter.

3.4. X-ray emitting gas and its dynamics

If the unabsorbed flux in the VMEKAL model (case CEI) is adopted, the X-ray (0.5-10 keV) luminosity is $L_x \sim 2.7 \times 10^{36} d_8^2\,\mathrm{ergs\,s^{-1}}$. The best-fit volume emission measure (EM) of the remnant in the CEI case is $f n_e n_{\mathrm{H}} V \sim 1.0 \times 10^{59} d_8^2\,\mathrm{cm^{-3}}$, where f is the filling factor of the X-ray emitting plasma; the EM value in the NEI case is a bit smaller. Based on the VLA observation (RM93), we approximate the remnant volume as a cylinder of a diameter $5'$ and a height $7'$. With $n_e \approx 1.2 n_{\mathrm{H}}$ assumed, the emission measure yields $n_{\mathrm{H}} \sim 1.5 f^{-1/2} d_8^{-1/2}\,\mathrm{cm^{-3}}$. The X-ray emitting mass is $M_x = 1.4 n_{\mathrm{H}} m_{\mathrm{H}} f V \sim 92 f^{1/2} d_8^{5/2} M_\odot$, which indicates that the emission is dominated by swept-up ambient matter. (The NEI case would correspond to 0.86 times the above gas density and mass.) The spectral fits show a trend of larger EM of the NW region than that of the SE region. This may imply that the NW part of the remnant gas is denser than the SE part.

The mean interior hot gas density n_{H} is much smaller than the environment H-atom density

$2\langle n(\mathrm{H}_2)\rangle$ inside the molecular cloud, indicating that a large amount of ambient matter does not act as X-ray emitting gas after being swept up or engulfed by the supernova blastwave. The explanation could be either that we are observing the hot, tenuous internal gas while the dense material near the rim has cooled down, or that the medium inside the cloud is clumpy and most of the X-ray emitting interclump medium (ICM) was evaporated from the clumps. The two mechanisms can both lead to the observed centrally brightened X-ray morphology, as we discuss below.

3.4.1. Cloud evaporation case

Here we use the self-similar solution incorporating cloud evaporation (WL91) to discuss the dynamics of SNR 3C 391. Because cloud evaporation slowly increases the interior density, the mean interior hot gas density could be a few times the postshock density. This gas can provide the centrally emitting thermal X-ray component observed "mixed morphology" remnants such as 3C 391 and others (Harrus et al. 1997, Harrus et al. 2001). The postshock temperature T_s can be derived from the observed X-ray emitting gas temperature $kT_x (\sim 0.52\,\mathrm{keV}$ in the CEI case) using a scaling factor

$$q = KT_x/1.27T_s, \tag{1}$$

where q and the energy ratio constant K (scaled by Sedov value) are dependent on C/τ (WL91). Here C is the ratio of the mass in the clumps to the mass of ICM, and τ is the ratio of the cloud evaporation time to the SNR's age. We follow RP96 and take $C/\tau \sim 3$-5. The velocity of the blastwave can be obtained from $v_s = (16kT_s/3\mu m_{\mathrm{H}})^{1/2}$ where the mean atomic weight $\mu = 0.61$, which then gives the dynamical age of the remnant $t = 2r_s/5v_s$. Since the SNR is complicated in morphology, we scale the radius with a mean value $(3')$ of the whole radio volume: $r_s = 3'r_3$. The hot gas density distribution is dependent upon the model parameters; for simplicity, however, we assume the mean interior density is twice the postshock density, which is broadly consistent with a range of profiles for the cloud evaporation model. Thus the undisturbed preshock ICM density n_0 is about $n_{\mathrm{H}}/8 \sim 0.2f^{-1/2}d_8^{-1/2}\,\mathrm{cm}^{-3}$. This density can also be estimated from the X-ray

luminosity L_x ($\sim 2.7 \times 10^{36} d_8^2$ ergs s^{-1}) using WL91's eq.(21) and it is thus in a consistent range ~ 0.1-$0.2 r_3^{-3/2} d_8^{-1/2}$. The explosion energy is given by

$$E = \frac{16\pi(1.4 n_0 m_H)}{25(\gamma + 1)K} \frac{r_s^5}{t^2}, \tag{2}$$

where the adiabatic index $\gamma = 5/3$. The results of the dynamical parameters obtained from the above relations are tabulated in Table 5. The explosion energy $(1.3$-$3.4) \times 10^{50}$ ergs is somewhat lower than the canonical value of 10^{51} ergs. The age estimate in RP96's evaporation model (~ 6-8×10^3 yr) is higher than that obtained here (~ 4-$5 \times 10^3 r_3 d_8$ yr), majorly because they used a larger-than-average radius of remnant. RM93 used a Sedov model with a high preshock density, so their estimate of age is rather large ($\sim 1.7 \times 10^4$ yr).

3.4.2. Radiative rim case

In this case we assume the clumpy mass is not important and the mean molecular density $\langle n(H_2) \rangle$ would correspond to a uniform undisturbed hydrogen density $n_0 \sim 30$ cm^{-3}. The radius of the SNR at the beginning of the radiative pressure-driven snowplow (PDS) stage is given by (Cioffi, McKee, & Bertschinger 1988)

$$r_{PDS} = 14.0 E_{51}^{2/7} n_0^{-3/7} \zeta_m^{-1/7} \text{ pc}, \tag{3}$$

where ζ_m is the metallicity factor and is close to unity for normal abundances. Adopting an explosion energy $E_{51} \equiv E/(10^{51}$ ergs$) \sim 1$, we have $r_{PDS} \sim 3.3$ pc, which is smaller than the remnant's radius $r_s \gtrsim 6 d_8$ pc (here a radius $2.5'$ of the NW radio shell is adopted). Thus, we expect at least the NW part of the SNR, which appears to be in contact with the dense cloud, to have already approached the PDS phase. In fact, the X-ray emission in the NW does not extend out to the radio shell as it does in the SE. This is similar to what is observed in W44, in which the remnant has entered the radiative phase, shutting down the X-ray at the radio shell (Harrus et al. 1997). The newly detected near-infrared [Fe II] and the mid-infrared 12-18 μm emission reveals the radiative shell of 3C 391, particularly in the NW rim (Reach, Rho, & Jarrett 2001). We thus

assume that the shell of 3C 391 has cooled sufficiently to have reached the radiative phase. In this case the hot interior of the remnant drives the cooled shell to expand and is responsible for the centrally enhanced cooling (e.g. Cioffi et al. 1988). Although ignored here, the effects of thermal conduction enhance this process through smoothing of the interior temperature profile (Cox et al. 1999, Shelton et al. 1999).

The postshock temperature should be lower than that for the Sedov case: $kT_s < 0.77kT_x \sim 0.4\,\mathrm{keV}$; the shock velocity v_s is then slower than $\sim 580\,\mathrm{km\,s^{-1}}$. In the PDS stage, r_s and v_s follow the formulae (Cioffi et al. 1988)

$$r_s = r_{\mathrm{PDS}} \left(\frac{4t}{3t_{\mathrm{PDS}}} - \frac{1}{3} \right)^{3/10}, \tag{4}$$

$$v_s = v_{\mathrm{PDS}} \left(\frac{4t}{3t_{\mathrm{PDS}}} - \frac{1}{3} \right)^{-7/10}, \tag{5}$$

where $v_{\mathrm{PDS}} = 413 n_0^{1/7} \zeta_m^{3/14} E_{51}^{1/14}\,\mathrm{km\,s^{-1}}$ and $t_{\mathrm{PDS}} = 1.33 \times 10^4 E_{51}^{3/14} n_0^{-4/7} \zeta_m^{-5/14}\,\mathrm{yr}$. From the above, one has

$$E_{51} = \left(\frac{r_s}{14\,\mathrm{pc}} \right)^{98/31} \left(\frac{v_s}{413\,\mathrm{km\,s^{-1}}} \right)^{42/31} n_0^{36/31} \zeta_m^{5/31}, \tag{6}$$

which yields $E_{51} < 9.2(r_3 d_8)^{98/31}$, which is reasonable although it offers a weak overall constraint. From Cioffi et al. (1988), the age of the remnant can readily be obtained:

$$t = 3.3 \times 10^3 \left(\frac{r_s}{14\,\mathrm{pc}} \right) \left(\frac{v_s}{413\,\mathrm{km\,s^{-1}}} \right)^{-1} \left[3 + n_0^{-10/31} \zeta_m^{-10/31} \left(\frac{r_s}{14\,\mathrm{pc}} \right)^{-10/31} \left(\frac{v_s}{413\,\mathrm{km\,s^{-1}}} \right)^{40/31} \right] \mathrm{yr} \tag{7}$$

which yields $t > 4.3 \times 10^3 r_3 d_8\,\mathrm{yr}$. If we use E_{51} as a parameter, then the present shock velocity is $v_s \sim 110 E_{51}^{31/42}(r_3 d_8)^{-7/3}\,\mathrm{km\,s^{-1}}$ and the remnant age is $t \sim 1.9 \times 10^4 E_{51}^{-31/42}(r_3 d_8)^{10/3}\,\mathrm{yr}$.

The cloud evaporation and the radiative rim mechanisms both produce acceptable dynamical parameters. A final judgment between them may depend on higher resolution observations with *Chandra* and *XMM-Newton* which may, for example, yield fine radial brightness and temperature profile or reveal smaller scale features that might support the clumpy ISM scenario.

4. Conclusion

We have investigated the spatial and spectral properties of the SNR 3C 391 using *ASCA* SIS data. The CEI and NEI spectral fits indicate that the hot gas within the SNR has basically reached ionization equilibrium. The hydrogen column density in the direction of the NW portion of the SNR is higher than that of the SE portion, in agreement with the location of the molecular cloud to the NW. The comparison of the hydrogen column and X-ray hardness between the NW and SE portions supports the NW-to-SE breakout scenario, as suggested by earlier observations of this SNR. The much lower mean density within the SNR than the immediate ambient cloud density and the centrally brightened X-ray morphology can be explained either by an SNR evolving in a clumpy cloud inside of which gas is evaporated from the engulfed cloudlets, or by an SNR which has entered the radiative stage with the interior gas still hot, but with the rim material cooled down.

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Table 1a: Summary of observations (used)

Seq. No.	Instrument	clocking mode	exposure
ad51017000s000102h	SIS0	4-CCD	36 s
s000202h	SIS0	4-CCD	10,479 s
s000302m	SIS0	1-CCD	23,927 s
s000502m	SIS0	4-CCD	26 s
s000602m	SIS0	1-CCD	94 s
ad51017000s100102h	SIS1	4-CCD	10,594 s
s100202m	SIS1	1-CCD	24,056 s
s100402m	SIS1	4-CCD	26 s

Table 1b: Summary of net count rates (in counts s^{-1})

CCD chips	whole	NW	SE
SIS0 1-CCD	$(18.7 \pm 0.3) \times 10^{-2}$	$(5.3 \pm 0.2) \times 10^{-2}$	$(7.2 \pm 0.2) \times 10^{-2}$
SIS1 1-CCD	$(15.2 \pm 0.3) \times 10^{-2}$	$(4.9 \pm 0.1) \times 10^{-2}$	$(5.8 \pm 0.2) \times 10^{-2}$
SIS0 4-CCD	$(17.3 \pm 0.4) \times 10^{-2}$	$(5.4 \pm 0.2) \times 10^{-2}$	$(6.3 \pm 0.3) \times 10^{-2}$
SIS1 4-CCD	$(13.0 \pm 0.4) \times 10^{-2}$	$(4.3 \pm 0.2) \times 10^{-2}$	$(4.5 \pm 0.2) \times 10^{-2}$

Table 2: VMEKAL (CEI) fitting results with the 90% confidence ranges

	whole	NW	SE
$fn_e n_{\mathrm{H}}V/d_8^2$ $(10^{58}\,\mathrm{cm}^{-3})$	$10.39^{+1.95}_{-1.75}$	$4.16^{+1.46}_{-1.20}$	$3.71^{+1.11}_{-0.93}$
kT_x (keV)	0.52 ± 0.03	$0.52^{+0.05}_{-0.04}$	0.51 ± 0.03
[Mg/H]	$1.36^{+0.18}_{-0.17}$	$1.16^{+0.35}_{-0.30}$	$1.50^{+0.31}_{-0.27}$
[Si/H]	1.00 ± 0.10	$0.81^{+0.17}_{-0.14}$	$1.07^{+0.17}_{-0.19}$
[S/H]	0.67 ± 0.14	$0.53^{+0.23}_{-0.21}$	$0.63^{+0.26}_{-0.22}$
N_{H} $(10^{22}\,\mathrm{cm}^{-2})$	$3.03^{+0.10}_{-0.11}$	$3.34^{+0.17}_{-0.18}$	2.96 ± 0.14
$F(0.5\text{-}10\,\mathrm{keV})$ $(\mathrm{ergs\,cm^{-2}\,s^{-1}})$	4.7×10^{-12}	1.5×10^{-12}	1.7×10^{-12}
$F^{(0)}(0.5\text{-}10\,\mathrm{keV})$ $(\mathrm{ergs\,cm^{-2}\,s^{-1}})$	3.5×10^{-10}	1.4×10^{-10}	1.2×10^{-10}
χ^2/d.o.f.	349/230	125/108	201/118

Here f denotes the filling factor of the hot gas, F the absorbed flux,

and $F^{(0)}$ the unabsorbed flux.

Table 3: VNEI fitting results with the 90% confidence ranges

	whole	NW	SE
$fn_e n_{\mathrm{H}}V/d_8^2$ $(10^{58}\,\mathrm{cm}^{-3})$	$7.38^{+1.46}_{-1.09}$	$3.50^{+1.08}_{-0.88}$	$1.99^{+0.90}_{-0.44}$
kT_x (keV)	$0.59^{+0.03}_{-0.01}$	$0.57^{+0.04}_{-0.05}$	$0.63^{+0.07}_{-0.03}$
$n_e t$ $(10^{13}\,\mathrm{cm}^{-3}\,\mathrm{s})$	$0.85^{+\infty}_{-0.10}$	$3.86^{+\infty}_{-0.52}$	$3.76^{+\infty}_{-0.41}$
[Mg/H]	$1.37^{+0.23}_{-0.19}$	$1.25^{+0.46}_{-0.33}$	$1.64^{+0.21}_{-0.40}$
[Si/H]	$1.22^{+0.15}_{-0.12}$	$1.02^{+0.23}_{-0.19}$	$1.38^{+0.27}_{-0.24}$
[S/H]	$0.75^{+0.17}_{-0.16}$	$0.59^{+0.29}_{-0.26}$	$0.68^{+0.32}_{-0.29}$
N_{H} $(10^{22}\,\mathrm{cm}^{-2})$	2.90 ± 0.07	3.33 ± 0.15	$2.70^{+0.16}_{-0.06}$
$F(0.5\text{-}10\,\mathrm{keV})$ $(\mathrm{ergs\,cm^{-2}\,s^{-1}})$	4.8×10^{-12}	1.5×10^{-12}	1.8×10^{-12}
$F^{(0)}(0.5\text{-}10\,\mathrm{keV})$ $(\mathrm{ergs\,cm^{-2}\,s^{-1}})$	2.3×10^{-10}	1.1×10^{-10}	6.4×10^{-11}
χ^2/d.o.f.	359/229	133/107	201/117

Here f denotes the filling factor of the hot gas, F the absorbed flux,

and $F^{(0)}$ the unabsorbed flux.

Table 4: Results of simultaneous VMEKAL fitting

for NW and SE, assuming the same kT_x

and the same N_{H}, respectively.

	NW	SE
kT_x (keV)	$0.51^{+0.04}_{-0.02}$	
N_{H} ($10^{22}\,\mathrm{cm}^{-2}$)	3.36 ± 0.12	$2.95^{+0.10}_{-0.11}$
$f n_e n_{\mathrm{H}} V / d_8^2$ ($10^{58}\,\mathrm{cm}^{-3}$)	$4.35^{+0.84}_{-0.75}$	$3.60^{+0.67}_{-0.61}$
χ^2/d.o.f.	$326/233$	
N_{H} ($10^{22}\,\mathrm{cm}^{-2}$)	$3.13^{+0.08}_{-0.09}$	
kT_x (keV)	0.57 ± 0.03	0.48 ± 0.02
$f n_e n_{\mathrm{H}} V / d_8^2$ ($10^{58}\,\mathrm{cm}^{-3}$)	$3.00^{+0.49}_{-0.37}$	$4.82^{+0.73}_{-0.68}$
χ^2/d.o.f.	$337/233$	

Table 5: Dynamical parameters for the

evaporation model of WL91

$C/\tau^{\dagger}$	3-5
$K^{\ddagger}$	0.385-0.189
$q^{\ddagger}$	0.372-0.143
kT_s (keV)	0.42-0.54
v_s ($\mathrm{km\,s}^{-1}$)	590-670
r_s (pc)	$7.0 r_3 d_8$
t ($10^3\,\mathrm{yr}$)	$(4.6\text{-}4.0) r_3 d_8$
E ($10^{50}\,\mathrm{ergs}$)	$(1.3\text{-}3.4) f^{-1/2} r_3^3 d_8^{5/2}$

$\dagger$ following RP96

$\ddagger$ adopted from WL91

5.   Figure captions

Fig. 1.— The SIS X-ray spectra of 3C391 fitted with the VMEKAL model. The three energy ranges (ER) are labelled, in which the narrow band images are produced.

Fig. 2.— Two dimensional confidence contours for the NW and SE regions of 3C 391. The contours from inner to outer correspond to $\Delta\chi^2 =$2.30 (68%), 4.61 (90%), and 9.21 (99%).

Fig. 3.— The X-ray images produced using SIS0 data. Panel a is the hard (2.6-10 keV) emission gray-scale image overlaid with the soft (0.5-2.6 keV) emission contours. The three circles in panel a designate the areas from which the SIS spectra are extracted. Panels b and c display the gray-scale images of soft and hard emission, respectively, overlaid with the dashed contours of 1.5 GHz radio emission (from Moffett & Reynolds [1994]). Panels d, e, and f are the narrow band gray-scale images and solid contours of Mg Heα (1.2-1.5 keV), Si Heα (1.7-2.0 keV), and S Heα (2.3-2.6 keV) emissions. In panel f the image is also overlaid with the dashed radio contours. The seven levels of solid contours are linear between the maximum and 20% maximum brightness. The two cross labels in each panel denote the OH maser points (Frail et al. 1996).